Discussion before the Wireless Section, 3rd December, 1930.

Mr. G. Shearing: The paper is an important contribution to our knowledge of short-wave aerial arrays. Especially valuable is the manner in which the author has dealt with the practical design and economics of the aerial systems. I note that the results obtained by the Post Office Engineering Department confirm the conclusions of other workers, notably Franklin and T. L. Eckersley in this country, as regards the value of low-angle radiation. The Naval Signal School, Portsmouth, some time ago carried out a series of experiments using small arrays on transmissions from Horsea at varying angles to the horizontal, and although in a few isolated cases good received signal strengths were recorded for higher-angle radiation, the average of all the reception results reported from the Far East was greatly in favour of lower-angle radiation, making an angle with the horizontal certainly not greater than 15° for wavelengths between 15 and 40 m. On pages 292 and 294 the author infers that the earth is a perfect conductor, whereas many experimenters have assumed that the earth has considerable resistivity at these high frequencies. For the aerials described, with the lower ends at a height of the order of one-quarter of a wavelength from the ground, I should have expected the earth loss to be appreciable, and I have usually assumed that this height should be of the order of one wavelength or more above the ground for reasonable reduction of earth losses. I should like to ask whether the author has carried out any actual radiation-resistance measurements on the aerials referred to in the curves of Fig. 12, for comparison with the calculated values plotted in the figure. The reference on page 295 to lateral deflection for the case of a narrow beam refers, I assume, to the displacement of a given beam from the great circle bearing normal to the array. It is conceivable, especially for transmissions east and west where change from a light to a dark zone may occur, that lateral dispersion of the beam may be produced, and I should

like to know whether any evidence of this has been obtained for the transatlantic or other short-wave services, whereby the service area for the main beam is greater than the theoretical area as calculated from the angle of the beam at the actual array. The portion of the paper dealing with the economical size of aerial array is interesting, but I suggest that the author should expand the second paragraph of this section so as to deal more fully with the comparison of aerial arrays. As regards the relative effects of reflector curtains at three-quarters and one-quarter of a wavelength from the exciter curtains, I am not clear whether the reflector curtain has the same total width as the exciter wires. Perhaps the author will state the spacing between the reflector wires. In connection with the improvement obtained by increase of the number of reflector wires, is the explanation that as the wires come closer together the phase of the induced currents becomes more uniform throughout the curtain? Also, does the Post Office Engineering Department contemplate using reflector curtains with three-quarter wavelength spacing from the exciter wires? With regard to the interesting polar diagrams shown in Figs. 23 and 24, has the horizontal type "T.W." array with a calculated direction of radiation inclined at 10° to the horizontal proved to be more effective than the vertical type with a direction at 0° to the horizontal? The fact that the open type of transmission line can be made efficient by arranging for a perfectly symmetrical design throughout the aerial system is important, in view of the considerable saving which results in the capital cost of the aerial feeder system.

Dr. R. L. Smith-Rose: I should like to join Mr. Shearing in expressing my appreciation of this paper, on the subject of which very little has been published in this country. One is apt to obtain the impression that all the work in connection with antenna arrays is being done abroad, since most of the published work has emanated from Germany, Japan and America. The paper brings to light the second of two important advantages associated with the use of short waves in radio communication. The first advantage is that the radiation efficiency of a transmitting aerial is much higher for short than for long waves, and the second is that one can effectively increase the useful radiation from the transmitting aerial by employing an antenna array. From the figures given in the paper it appears that a power ratio of the order of 100 to 250 times could be obtained with a suitably designed antenna array, i.e. a 10-kW beam station using a short wavelength becomes equivalent to a 1 000- or 2 000-kW station distributing its radiation in all directions. A considerable amount of theoretical work underlying the design of antenna arrays has been done in this country at the National Physical Laboratory under the auspices of the Radio Research Board, and I would suggest that reference to some of this—particularly to a group of three papers recently published in the *Journal**—be inserted in the paper. In the first of these, by Messrs. R. M. Wilmotte and J. S. McPetrie, the substance of Fig. 15 of this paper was contained, and it was definitely pointed out that the optimum spacing between an excited antenna wire and the reflector wire for maximum forward radiation was either 0·33 or 0·85 of a wavelength instead of the previously accepted values of one-quarter or three-quarters of a wavelength. This was a theoretical deduction, and I am interested to note that it has been borne out by some German theoretical work and experimentally confirmed by two American investigators. I would also point out that additional experimental confirmation was given by Messrs. L. S. Palmer and L. L. K. Honeyball* in a paper published in the same month as the paper by Englund and Crawford appeared in America. In view of the fact that the optimum distance has been found to be one-third of a wavelength, I should like to ask whether the author has carried out any experimental work with this spacing. In the case of the arrays given in the paper the spacing is definitely referred to as one-quarter of a wavelength, and I am at a loss to understand what advantage, if any, is gained by this arrangement. In view of the confirmation of the fact that the optimum distance is one-third of a wavelength, it will be interesting to see whether arrays will in future be built with this spacing instead of one-quarter of a wavelength. I share Mr. Shearing's views on the effect of the conductivity of the earth. During the past few years our knowledge of the conductivity of the earth and of its effect on radio-wave propagation has considerably increased and it is possible to take the earth into account in making calculations on antenna systems. Incidentally, Wilmotte in a very recent paper† stated that he had been able to allow for the effect of the conductivity of the earth as measured on the site of the transmitting station, and thus to correct the calculated polar diagrams and obtain better agreement with his experimental results. With regard to the question of the best angle of elevation at which to project the beam, it at first seems obvious that in order to send a beam over a distance of several thousand miles it is necessary to project it at an angle of 10° or 20°, or more, to the horizontal. On further consideration, however, the reason for expecting the optimum direction of radiation to be approximately horizontal becomes apparent. For example, Fig. A shows a section drawn to scale of the earth with its radius of 4 000 miles, and the ionized layer at a distance of 100 miles above it. A wave starting from the transmitting station at a large angle to the horizontal will come down after travelling 200 or 300 miles. On the other hand, a wave which leaves in a horizontal direction passes the earth again at grazing incidence, and, after a second reflection, comes down at a receiving station approximately 3 500 miles away. This is about the distance between London and New York. Thus the wave which stands the most chance of getting from London to New York is one which leaves in a direction approximating to the horizontal. Any other wave would be reflected many more times on its passage, and would suffer more loss by the repeated reflections at both the earth and the ionized layer. As the earth is an imperfect conductor it is not possible to project a beam exactly horizontally, and it is therefore necessary to have an elevation of a few degrees, just sufficient to free the radiation from the effects of the finite conductivity of the earth. I do not

* *Journal I.E.E.*, 1928, vol. 66, pp. 949–967.

* *Journal I.E.E.*, 1929, vol. 67, p. 1045. † *Ibid.*, 1930, vol. 68, p. 1191.

quite understand the author's use of the term "radiation resistance" in his reference to the work of Pistolkors. I gather that Pistolkors defines radiation resistance as the radiated power divided by the square of the current; but in view of this, and taking into account Fig. 12, I am at a loss to understand why it was considered an advantage to choose the point at which the radiation resistance was a minimum. Consideration of the definition leads me to think that the condition of maximum radiation resistance is what is required. I use the term here in its broadest sense, taking it to include the effect of neighbouring wires and of the earth. Perhaps the author could enlighten me on this point. From Fig. 7 it would appear that the quarter-wave aerial gives the same radiation in a horizontal plane as a half-wave aerial, but this is surely only true if the current in the former case is twice that in the latter. I suggest that Fig. 24 be rotated through 90° so as to be presented in the same way as Fig. 23.* I gather that one of the great advantages of the type of array which the author has developed is that the use of high and expensive masts is dispensed with, and one is able to effect a great economy in the general construction of the array. Incidentally, on close study of the paper one appreciates that the author has done great service in designing an economical and efficient type of self-supporting mast. What are the relative advantages of the horizontal as compared with the vertical type of array? I am unable to draw a definite conclusion from the paper on this point.

* This has been done for the *Journal*.

Col. A. S. Angwin: It is refreshing to see a mathematical treatment of this subject applied so directly to economic considerations. The author stresses the economic aspect of the large area of site occupied by array systems, particularly where concentration of services and alternative wavelengths have to be considered. In the past the tendency in laying down transmitting and receiving aerial systems has been to prolong them in long lines in order to prevent the possibility of mutual interference. The tendency now is in the direction of erecting more than one array on the same supporting structure, and it is interesting to note that the Post Office Engineering Department have now two groups of arrays in which this device has been successfully adopted. One, a vertical array for 42·92-m wavelength, has contained within it a horizontal array for a 30-m wavelength; the other, a 33·5-m vertical array, has suspended within it on the same masts and cross-arms a horizontal array with a 25-m wavelength. The actual loss measured on the second of these combined arrays is only of the order of 0·5 decibel, a negligible loss compared with the saving in cost. The author deals with the question of height of arrays as affecting signal strength at a distance. The fortunate circumstance that two 820-ft. masts were available at the Rugby radio station enabled a large-scale experiment to be carried out which has some bearing on the point mentioned in the paper. Utilizing these masts to carry a triatic, a combination of vertical and horizontal radiating elements was erected which consisted of 64 half-wave horizontal and 128 half-wave vertical elements, arranged in one large network about 1 020 ft. long, 400 ft. in depth and raised 50 ft. above the ground. These aerials could be fed simultaneously, so that they radiated from both the horizontal and vertical elements, or alternatively the horizontal and vertical elements could be fed independently. The wavelength was 27·8 m, and a comparison was made with an aerial using the same wavelength and the same number of horizontal elements, but erected on 180-ft. masts. It was interesting to observe that, in spite of its much greater height, the actual results received in Australia from the first aerial with the horizontal elements alone excited were slightly worse than those obtained from the low aerial system, and the efficiency of the horizontal and vertical aerials together on the high masts was definitely worse than that of the horizontal system on the lower masts. This emphasizes the point to which the author refers, that beyond a certain limit the intensive narrowing of the beam may tend to be prejudicial to, rather than to improve, the effect received at a distance. I am not clear with regard to the assumption made by the author that the earth is a perfect conductor. Measurements have been made of the conductivity of the earth at the frequencies dealt with in this type of array, and figures varying from 6° to 10° are given for the wave tilt. One might assume from this that in the case of horizontal-type arrays there would be some measurable field on the ground, but the author's experiments indicate that this is not so. I think that the apparent contradiction between these two facts should be the subject of further research, or at any rate of mathematical analysis. More information as to the

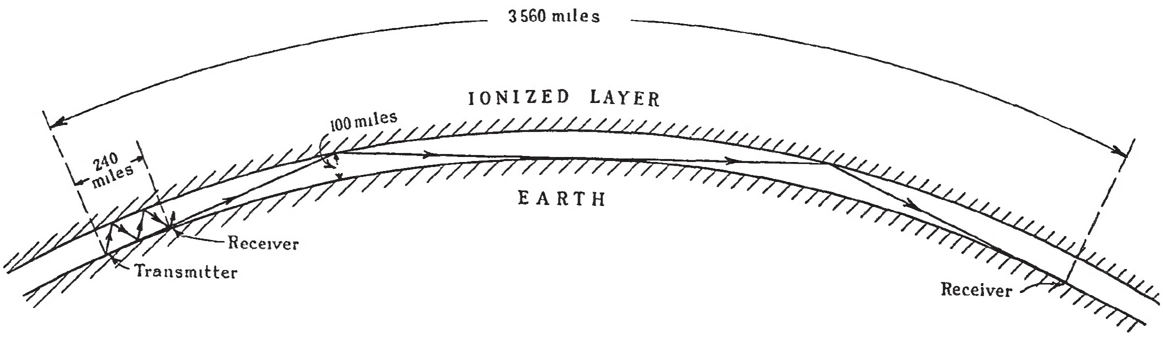

FIG. A.—Section of Earth, radius 4 000 miles, and ionized layer at a height of 100 miles, showing the paths of waves between a transmitting station, and two receivers at distances of 240 and 3 560 miles.

apparent values of the earth's conductivity at high frequencies would be a valuable contribution to the subject.

Captain J. W. S. Dorling: I should like to ask two questions, the first of which is connected with the economics of the subject. The author points out that a gain in signal strength may be obtained by increasing the height of the masts and using a more extensive array. Has he considered the economic aspect of getting the same increase of signal strength by an increase of power at the transmitter? Secondly, has he considered the question of widening the beam and thus communicating with a zone rather than with a definite point on the earth's surface? The case I have in mind is the ship-to-shore telephony services in operation on the North Atlantic route. It seems to me that in some instances a wide-angle beam would be an advantage for getting signals to the ships, and possibly for receiving signals from those ships. It might perhaps result in a decreased cost of the apparatus to be installed in the ship, or, what is even more important in some cases, a less complex apparatus.

Mr. F. S. Barton: We at Farnborough were associated with the work done there by Mr. Wilmotte to which reference is made in the paper, and it would be interesting to us to know how valuable this was and whether more work of a similar type will be necessary. The author regards arrays almost entirely from the point of view of how strong a signal he can obtain for a given amount of money, whereas in the Royal Air Force we want mobility also. The earlier types of arrays and transmission lines do not seem to be adaptable to mobile use. The introduction of the open-wire transmission lines and quarter-wave matching lines described by the author, however, seems to make possible the use of an array in a mobile station. Inspired by the work of the Post Office Engineering Department, we have made a brief study of the subject and have erected a simple Koomans array consisting of four half-wave dipoles, built up almost entirely from mobile-station equipment. This attempt was made primarily in order to find out whether one could realize in practice, with this simple mobile equipment, a calculated design, and secondarily to ascertain whether this design was of any use for services of a mobile nature.

Mr. A. J. Gill: I should be glad of further information regarding the relative advantages of the various arrays. A peculiar feature of the Sterba array is that it is a closed circuit and can thus be energized by low-frequency currents in order to prevent the formation of sleet under certain weather conditions. With regard to the Koomans array, especially the horizontal pattern, has the author considered the possible advantage of placing the vertical feeders a little nearer together, and allowing the ends of the aerial to overlap? This would increase the current concentration and enable more stacks of aerials to be placed in a given span between masts. I think that there is a possibility of increasing the efficiency of the mast arrangement by this method. In some of the calculations for Fig. 13 the author has taken the value of the dead-loss resistance of a half-wave element to be about 25 ohms. I should like to ask what reasons he has for assuming this rather high value and what effect any variation of the figure will have upon the results. With regard to the multi-wire transmission line shown in Fig. 26, I suggest that a considerable advantage would be gained by transposing the lines. The impedances of the individual wires apparently amount to about 500 ohms in the case of inner wires, and 620 ohms in the case of outer wires. This should lead to uneven distribution of current in the four wires comprised in each of the lines. I should like to know what accuracy can be assumed in the figures given for the efficiency of lines. In our early work with transmission lines, having, as we thought, balanced the line, we attempted to take some measurements; it was found, however, that apparently far more power was being received at one end of the line than was being fed in at the other, and we had to abandon the attempt. The results given in the paper are apparently based on certain calculations of the value of Z, and I should like to know the author's estimate of the accuracy of these.

Squadron Leader D. H. de Burgh: The point at issue is the efficiency as opposed to the directional properties of the array. At Farnborough I am using an array consisting of three ordinary mobile masts with guys, ordinary telegraph insulators (which the author regards as not good for this purpose), and 200-lb. wire; the preliminary results with this arrangement appear to show that the wavelength of the array is that for which it was designed and that the distance apart of the matching lines agrees with the calculated value. There is a discrepancy, however, in that a current node exists about 3 ft. from the correct position at the end of the matching lines. Although this does not appear to make much difference to the current in the array itself, I naturally cannot get exactly equal currents in the line. The discrepancy could probably be corrected by adjusting the length of the half-wave lines joining the matching lines to the two halves of the array. In view of the fact that there may be some doubt as to the calculated value of the impedance of radio transmission lines, what is the present position regarding the possibility of measuring the impedances of such lines at high frequencies?

Mr. F. C. Carter (*communicated*): There are one or two points in the paper on which I should like to comment. In the first place, when comparing various methods of grouping the radiating elements in the several array systems the author assumes that the same current is present in the centre of each element. This may be true for certain types of arrays, such as the horizontal Koomans shown in Fig. 3, where the pairs of horizontal conductors constitute equal parallel resistive loads at the bottom of the vertical feeders, and therefore (neglecting the small ohmic loss in these feeders) all carry equal currents. In other types of arrays, viz. the Sterba (Fig. 4) and Marconi-Franklin (Fig. 2), certain of the antennæ are in series with one another, so that those nearer the energizing source carry larger currents than those more remote It is obviously difficult to determine this distribution in the case of a vertical-type array, but from some tests made on an 8-section double Bruce array the current in the radiators near the energizing feeder was found to be approximately three times that in the outermost radiator. If such an unequal current distribution occurs

in a vertical-type array, there is a substantial reason for limiting the economic height of beam arrays, since the higher the radiators the less effective they become. The author, in common with many other writers on this subject, tacitly assumes that the best vertical spacing of the tiers of an array is one half-wavelength. This is probably because with such a spacing it is easy to arrange the bends in the wires so that all the radiators are correctly phased. As an alternative to this half-wavelength spacing, I suggest that a vertical spacing of one-quarter wavelength is worthy of consideration with a horizontal-type radiator. This could readily be accomplished by using one-half of a double Bruce type array (shown in Fig. 27) turned through 90° and energized at the bottom. A number of such panels side by side would comprise the array. By suitably adjusting the length of the uppermost vertical element another closed-loop type array is obtained. By these means twice as many radiators can be arranged while still using the same height of tower. The spacing of the reflector curtain behind the array has long been a controversial subject, and perhaps the author dismisses it rather lightly. Consider a simple array and reflector; the field in front of the array is the sum of two vectors, one proportional to the current in the directly energized radiators, the other proportional to the current in the reflectors and displaced from the first vector by an angle depending on (*a*) the distance between the curtains and (*b*) the phase relationship of the currents in the aerial and reflector. At distances of the order of one quarter-wavelength the current in a radiation-excited reflector increases rapidly with a small decrease in spacing, with only a small resultant change in phase of the current, provided that the reflector is correctly tuned. It is thus possible for the resultant vector sum to be greater than that obtained when the spacing is one quarter-wavelength. I have carried out some experiments which, although unfinished, showed the optimum spacing for maximum forward radiation to be 0·21 wave-length. It is of interest to note that Tatarinoff* advocates a spacing of 0·2 wavelength for the rear reflector of a parabolic reflector. The major portion of the paper deals with transmitting arrays, and receiving arrays are different in many respects Among other points it would appear that there is an optimum width of receptive angle in the vertical plane, determined, of course, by the number of tiers. Perhaps the author would indicate whether he thinks it preferable to make this angle nearly zero, or alternatively, to use a beam having a wide receptive aperture in the vertical plane—as advocated by Schelleng.† A more convincing method of drawing Fig. 13 would be, I think, to show the effect of a similar number of radiating elements distributed either vertically, horizontally or in planes.

Mr. H. Chireix (*communicated*) : The aerial referred to by the author as the "Sterba" type is covered by my own patent. I cannot agree that a line consisting of coaxial conductors can cost five times as much as one having two parallel conductors. Moreover, I myself had already noticed the critical length of the wires which constitute the component parts of reflectors.

* *Zeitschrift fur Hochfrequenztechnik*, 1926, vol. 28, p. 117.
† *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 913

Captain P. P. Eckersley (*communicated*): I will ask the author some purely economic (as opposed to purely technical) questions. I am encouraged to do so since he has expressed the results of his equations in pounds and shillings. The economic answer would seem to be most logically expressed in terms of the cost of establishing a field of sufficient strength at the point of reception. The design of aerial is surely only one of many factors in this calculation. I suggest that the cost of the site for the station, the cost of power, the cost of maintaining the land lines, and the cost of maintaining and building the aerial structure, should all be taken into consideration, and the proportion which the cost of each bears to the total expenditure should determine its importance in the total economy considerations. Obviously, also, the field at a distance is proportional both to the radiation efficiency of the aerial (useful power divided by the power in the aerial) and to the power input to the transmitter. With a given aerial and given conditions, the field at a distance is increased directly as the power is increased. Would it be better to build a less efficient aerial and employ more power, or vice versa? (It is obviously the beam aerial that is here referred to, and the term "efficiency of aerial" refers to the efficiency of a beam aerial.) Thus, while the rather complicated mechanical design of aerial described may make the device, as such, so much more efficient, economically and technically, in creating a field at a distance, might not transmitting stations, disposing of simpler aerials, requiring, however, greater power, be still more efficient when efficiency is defined as the cost of establishing a field at the point of reception? Further, if this more general definition of economy be adopted, is there so much to be gained by using the design of aerial described, seeing that it is probably more difficult to construct and maintain, although more economical to support? The answers to these questions would seem to indicate the real relative efficiency of transmitting stations considered as complete units. The aerial is, after all, a component of a station and perhaps a not relatively expensive component. It may merit less consideration than other components and may be made sufficiently efficient by using greater power. A contributor to the discussion asked why the radiation resistance increased as the end of the aerial was brought nearer to the ground, and why, if that were so, it was not desirable to bring the end near the ground. I hope the author will emphasize his answer to that question. It is remarkable that this point, fundamental to an appreciation of even the essence of this and other papers on aerial design, is so frequently missed or not understood. A clear explanation was first given by an American, Stuart Ballantine.

Mr. C. S. Franklin (*communicated*): Before I designed the aerials for the imperial beam stations I investigated theoretically their possibilities. Assuming only Huygens's principle of propagation from a plane wave-front of definite area, Neumann's formula for the field at a distance from an element of current, and that the current in the aerial could be treated as a uniform sheet, I plotted the field intensity for a spherical surface of large radius compared with the aerial. Integrating the mean square of this field for the whole surface gave

a figure proportional to the energy passing through it. By repeating this procedure for various types of aerial I obtained comparative figures for several forms of aerial of the total energy which must be radiated to produce equal fields in a particular direction. I chose for comparison an aerial in which the radiation is confined to a single wire of small length in comparison with the wavelength. The result of the calculations showed that for aerials of this type having an aperture in both directions of upwards of one wavelength, the energy magnification figure which could be obtained per square of wavelength was 9·6. Compared with a half-wave aerial this magnification figure was approximately 8·7. Calculations were made to find the effect of the current being concentrated in the several wires instead of treating an aerial as a uniform current sheet. These showed that no material change resulted, provided that the wires were half a wavelength or less apart, and, as regards the vertical distribution, that the points of maximum current in phase were not substantially more than half a wavelength apart. These figures were published in a paper* by Marchesi Marconi in 1924. In this investigation I did not take the earth effect into account, as it was at that time, and still is, a very controversial subject. If the effect is taken into account it will modify the polar curve of any particular aerial in the vertical plane to a degree depending on the constants chosen, but I do not think that it will alter materially the comparative figures between various aerials. Using the methods described, I find that the comparative gains of aerials B and D (Fig. 13) when used with reflectors are 14 and 17·4 decibels respectively. I have not completely investigated aerial C, of the same figure, but from an inspection of the modification of the polar curve due to the introduction of the second line of radiators half a wavelength in front and 180° out of phase I find the gain of C over B to be quite small. As aerial C is the one specially recommended by the author, I think it important to establish whether his figures are correct or not. At present I disagree with them. There is a type of beam array consisting of a row of radiating aerials the current in which is so phased that the propagation is along the line of the aerials. Such a system gives a radiation confined within a cone, and the angle depends upon the length of the line used. When each element is a single wire a considerable magnification or gain can theoretically be obtained. The author's "T.W." aerial with a reflector is partly of this type. When, however, the units in such an aerial instead of being single wires are multiples of wires having a considerable extension both horizontally and vertically, with respect to the wavelength, the gain obtained by these arrangements in line one behind the other soon becomes very small and for one wavelength extension the gain of 3 units over 2 is hardly worth while. If I am right, the author's economic argument fails. This argument also appears to be unsound from another point of view, because the relative cost of aerials C and D, which are of two different types, are compared. I think that it would be more useful to give the relative gains and costs of C and D with D converted to the same type as C but keeping the same height as before. The author, in his description of the "T.W." vertical type of aerial, mentions the radiation from the horizontal members. I believe I originated the scheme of folding a long wire so as substantially to suppress radiation from alternative half-wavelengths, and so obtain concentrated radiation in a direction at right angles to such a wire. This principle made it possible to extend the beam aerials vertically, and to obtain in a simple manner concentration in the vertical plane. A number of different aerials utilizing this principle have been designed, and the method adopted for the imperial beam stations was only one of several possible arrangements. The principal reasons for its adoption were:—(1) Practically all horizontal wires, and their attendant disturbing effects, were eliminated. (2) The design enables the feeder distribution system and attachment points to be standardized for a wide band of wavelengths. (3) Damage to one or two elements of the aerial does not shut the station down. Since the original beam-station aerials were designed developments have taken place which, while maintaining the above characteristics, give a more effective use of the area of the aerial and a much improved polar curve in the vertical plane. The "T.W." array described by the author partly makes use of this principle, but I do not think that any considerable suppression of radiation from the horizontal members is obtained. I agree that side radiation from these members will be small, but there will be considerable radiation at angles some 50° above the horizontal in both forward and backward directions, and this will cause the loss of a considerable amount of energy. These loops considerably modify the distribution shown in Fig. 23. The author's remarks on transmission lines are interesting, and I agree with him that these are as important as the aerial. I was responsible for the adoption of the concentric-tube feeder, and, although the cost was high, I think that the decision was justified. Before deciding upon the concentric-tube type of feeder for the beam stations, I made experiments with the open twin type of feeder and also the twin feeder in an earthed case. The open-type feeder was not adopted, principally because of its inherent instability, although reasonable efficiency could be obtained with it. The concentric-tube feeder, on the other hand, proved both efficient and stable. The concentric tube need not differ greatly from the twin open type as regards cost, as the feeder can be made in the form of wire cages. Practical considerations in many parts of the world, however, decided that the feeder should take the form of actual tubes. Mr. E. Green, who helped a great deal in the development of the aerials and feeders, worked out theoretically the properties of the latter and showed that the maximum and minimum values of impedance, voltage and current occur at quarter-wave intervals along the feeder; he also found that the impedance at points of maxima and minima was purely resistive. These facts were made use of in the feeder distribution system of the beam stations, and they enabled the impedance matching devices to be eliminated at certain junctions.

* *Journal of the Royal Society of Arts*, 1924, vol. 72, p. 607

Mr. E. Green (*communicated*) As I assisted Mr. Franklin during the development of the Marconi type of beam aerial and feeders, I should like to make a few comments on the following items in this paper.—

Reflectors.—The normal front-to-back ratio of field strength of an ordinary exciter curtain and properly adjusted reflector curtain should be 15 : 1 or more. The author's figure of 12 : 1 mentioned when the paper was read compares reasonably with this. Data obtained from the imperial beam stations are not very relevant as these reflector curtains were erected to calculated dimensions, when the data on reflector wires were more meagre than they are to-day, and it was not possible to do much experimental work on stations being erected to contract.

Transmission Lines.—Tables 1, 2 and 3, giving the efficiencies of open-wire lines feeding vertical and horizontal aerials, are interesting. They show the risk of having large unknown radiation losses on open-wire lines. The ordinary erecting engineer can hardly be expected to detect and correct such losses. I find the author's remarks and experimental results on multi-wire feeders rather puzzling. He states that he connected three similar, independent transmission lines in parallel, and found (as he expected) a gain in efficiency due to the lower ohmic resistance of the line. Assuming that in each case the line is correctly terminated, there should, however, be no difference in efficiency between a single 2-wire line and any number of similar lines connected in parallel. For example, if three lines are put in parallel the resultant line resistance (which may include both ohmic losses and insulator losses) is reduced to one-third of the value for a single line. But the surge impedance, and therefore the correct terminal load resistance, is also reduced to one-third of its value for a single line. Hence the ratio of load resistance to line resistance is unchanged, and therefore the efficiency should be unchanged. The author's example of a multi-wire line is not quite the same as a number of independent lines in parallel, on account of mutual reactions between the wires, but the figures given indicate that the same amount of copper put into a single-wire line would result in a higher efficiency. The surge impedance of the multi-wire line is given as 190 ohms. The line resistance of the multi-wire line cannot be less than $\frac{1}{4}R$, where R is the effective resistance of a single-wire line of the same gauge. If instead of the multi-wire line we put the same amount of copper into a single-wire line, its resistance would be $\frac{1}{2}R$, and its surge impedance at 9-in. spacing 550 ohms. Therefore —

$$\frac{\text{Ratio of load resistance to line resistance of heavy-gauge line}}{\text{Ratio of load resistance to line resistance of multi-wire line}} = \frac{550}{\frac{1}{2}R} \cdot \frac{\frac{1}{4}R}{190} = 1\cdot45$$

This means that the single-wire line of heavy gauge could be at least 1·45 times as long as the multi-wire line and yet give the same efficiency.

Impedance Matching Devices.—Patents Nos. 274970 and 282905 taken out by Mr. Franklin and myself in 1926 give various ways of matching impedance at the junction or termination of transmission lines. These include combinations of coils and condensers as well as the devices favoured by the author, i.e. the use of a portion of transmission line of appropriate surge impedance as a transformer. The elementary theory of transmission lines at radio frequencies which led up to these devices was published in 1928.*

* *Experimental Wireless*, 1928, vol 5, p 304

Mr. T. Walmsley (*in reply*): Several speakers have commented upon my assumption of a perfect earth for the purpose of calculating gains of arrays, and the suggestion is made that such an assumption is not justifiable. The question must therefore be asked: What is the alternative? Certainly not a perfectly insulating earth. From purely electrical considerations the dielectric constant and conductivity of the earth should be taken into account. Several disturbing factors, however, militate against the practical application of theoretical principles. Firstly it is questionable whether the dielectric constant of the earth for short waves is known with even approximate certainty; secondly, experimental investigators are not agreed that the value of the dielectric constant remains constant with change of wavelength*; thirdly, the moisture content of the earth affects both its conductivity and dielectric properties. Even assuming an exact knowledge of the constants of the earth, the practical difficulties encountered in calculating the polar diagrams for the purpose of comparing the gains due to various groupings of wires are very great. To instance but one difficulty—for each particular angle of elevation considered the amplitude and phase angle of the reflected ray changes. Unfortunately, nebulous theories and vague assumptions do not assist the practical designer. He is compelled to accept the most workable hypothesis and if that hypothesis yields results that accord reasonably well with observed facts, he is justified in his assumption as a practical expedient. Such is the state of affairs in the present case.

In reply to Mr. Shearing's queries I have not verified practically the curves of Fig. 12. The displacement of a given beam refers to deviation from the great circle bearing normal to the array; the few measurements made in America on the transatlantic Rugby beam show that the calculated width of the main beam agrees reasonably well with the actual width, but as far as I am aware there have been no extensive tests to prove this matter. With regard to Mr. Shearing's suggestion that fuller comparison of arrays should be made, he will probably find that by utilizing the curves of Figs. 13 and 14 and applying the other information given on page 304, he will be able to compare several types of array. In all arrays used by the British Post Office the reflector curtains have approximately the same total span as the exciting curtain. Usually the spacing between adjacent reflector wires is half a wavelength, but in some cases when two exciter curtains are used in conjunction with one reflector curtain the reflector wires are spaced one-quarter of a wavelength apart. Such an arrangement gives a slightly better reflector action, due probably to an increase in the product of current in each reflector wire and the number of the reflector wires. It is not anticipated that the Post Office Engineering Department will make a general practice of using a separation of three-quarters of a wavelength between exciting and

* J. P. Ratcliffe and F. W. G. White: *Philosophical Magazine*, 1930, vol. 10, p. 667; also N. J. O. Strutt: *Elektrische Nachrichten-Technik*, 1930, vol. 7, p. 387.

reflecting curtain when only one exciting curtain is used. With regard to the relative effectiveness of horizontal and vertical arrays, the evidence shows that, for a given capital expenditure, the horizontal type is the better.

Dr. Smith-Rose points out that credit should be given to Messrs. R. Wilmotte and J. S. McPetrie for their theoretical work, and I regret that inadvertently I omitted reference to their published papers which take priority to some of the papers of other investigators. With regard to the question of the best distance between a single reflector and a single exciter wire, some tests have been made by Mr. F. C. Carter of the Post Office Engineering Department. These are referred to later in the discussion. I have carried out some experimental investigations on the effect of making the spacing of reflector and exciting curtains a little greater or less than a quarter of a wavelength, but these tests were not exhaustive since, when it was ascertained that a 12 : 1 ratio of front to back field strength was obtainable with a quarter of a wavelength spacing, it was considered of little economic importance to proceed further with the matter. The problem of spacing of curtains is obviously different from that of spacing of two wires. Dr. Smith-Rose's remarks concerning Wilmotte's ability to correct the calculated polar diagrams seem to me to display an optimism not shared by Mr. Wilmotte himself. The views of Dr. Smith-Rose on the best angle of projection of a beam are interesting but hardly accord with fact. He appears to suggest that 3 500 miles is the distance of optimum signal strength, but the reports from ships steaming between England and America do not substantiate that belief; signal strength appears to be about equal over large areas. The reason why the minimum value of radiation resistance is taken is explained at the bottom of the second column on page 303. As the aerial is raised, the volume of the solid polar diagram decreases for a constant current value in the aerial and a constant field strength at a distant point in a horizontal direction. Thus the power input and hence the total radiation resistance decrease, whilst the distant field strength remains constant. I support Dr. Smith-Rose's suggestion to rotate Fig. 24 through 90°, and I have arranged to do this for the *Journal*. The query concerning the relative advantages of the horizontal and vertical types of array was answered in my reply to Mr. Shearing.

Colonel Angwin mentions the tests made at Rugby to compare two arrays similar in type, but one having eight lines of horizontal radiators, one above the other, and the second having four lines of horizontal radiators. In both cases the spacing between lines was half a wavelength, but the higher aerial had half the span of the lower. The same transmitter was used for the tests and, by means of a throw-over switch, the aerials were alternately energized at intervals of a minute or two. When all connections had been made, the lower array was shown to be definitely superior to the higher. The explanation probably lies in the fact that a greater gain is theoretically possible by increasing the span rather than the height, and is also due to the difficulty in feeding current into the upper radiators of an array.

The question, raised by Captain Dorling, of the economic advantage of increasing the power delivered into arrays in preference to building large arrays is one requiring careful consideration of all the factors involved —the cost of land, masts and transmitters; maintenance charges; the life of valves; the cost of staffing; and the nature of the radio service. Obviously each specific case requires separate consideration. The widening of a beam can, of course, only be affected by sacrificing the ratio of field strength in the primary direction to the power input. In general, for mobile Services the best policy would appear to be to build several arrays, having different orientations but fairly narrow beams. The experiments of Wilmotte, to which reference is made by Mr. Barton, were valuable inasmuch as they were unique and gave an approximate picture of vertical polar diagrams. It is, however, debatable whether additional tests are worth while.

The feature of the Sterba array, mentioned by Mr. Gill, which enables sleet to be removed is valuable in countries having a more severe climate than England. As far as I am aware, Wilmotte first suggested* that it would be better to suppress more than a half a wave in

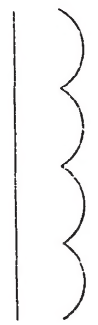

FIG. B —Envelope of current distribution in radiating wire.

the Franklin type of aerial and adopt the type of current envelope shown in Fig. B. In some types of aerial this idea is now effected by folding the wire of the aerial in various ways. Mr. Gill's suggestion possibly offers another means of achieving the same result. In effect, instead of suppressing the radiation from the end of the half-wave elements, he proposed to allow the ends of adjacent half-wave radiators to overlap for the purpose of augmenting the radiation. The idea is ingenious but, without practical test or theoretical analysis, I am unable to state whether improvement would result. The action of one radiator on an overlapping radiator might unfavourably effect the arrangement.

Mr. Gill raises the question of dead-loss resistance of half-wave elements. I confess that 25 ohms is more in the nature of an intelligent guess than an exact measurement. The value will vary according to the location of the array; the type of towers and their distance from the array; the value of the insulation of the array; and the arrangement of wires in the array. Eckersley† gave 14 ohms as the measured value of the dead-loss resistance of a quarter-wave aerial on a 300-metre wavelength. According to Mr. Barfield, who has kindly given me permission to quote the results of some tests made by him, the dead-loss resistance of a single-wire vertical aerial 6 metres high at 25 metres wavelength

* See Bibliography, (3) † *Ibid.*, (6).

(approx.) was 31 ohms. This value was obtained by measuring the total resistance of the aerial and deducting the calculated value of the radiation resistance. Other evidence from a reputable source seemed to me to justify the assumption of 25 ohms for the purpose of a comparison of different types of aerial. The effect of an increase or decrease in the value of r will, of course, depend upon the values of R_0 and R_N in the expression $N(R_0 + r)/(R_N + r)$. With regard to transposing lines, tests made on open-wire lines appeared to lead to the conclusion that little was to be gained thereby. Each transposition point produces in the line constants a change which may be sufficient to nullify any advantage. Rotation of the wires in each limb would remove the possible objection of variation of impedance With regard to the accuracy of the figures for efficiency of the open 2-wire transmission lines, I believe that, provided the out-of-balance currents are not too great, the figures are reasonably reliable. Mr. Gill mentions some of his tests on transmission lines. It is understood that the tests referred to were made on concentric tubes. An examination of the method of test and of the results obtained has convinced me that Mr. Gill's experiences cannot be advanced in refutation of the results on open transmission lines, quoted in the present paper With regard to the value of Z_0, reference to the Section on transmission lines will show that this quantity cancels out in calculations of efficiency.

The shifting of the position of the current nodes mentioned by Squadron-Leader de Burgh is a common experience. In the case quoted the cause is probably lack of electrical symmetry in the array, owing to the presence of the mast stay-wires As far as I am aware, there is no reliable field apparatus for measuring line impedances at radio frequencies of the order of 2×10^7 cycles.

The assumption of equal currents in the various radiators, to which reference is made by Mr. Carter, seems to be necessary for comparison purposes, particularly as the ratio of E to $\sqrt{P}$ is not greatly affected by appreciable variations in the relative current values in different radiators. For example, suppose an 8-wire vertical type of array has the following current values in adjacent wires, counting from one end and taking arbitrary units—1 : 2 : 3 · 4 : 4 : 3 : 2 · 1. The radio $E/\sqrt{P}$ may be represented by $\Sigma I/\sqrt{[\Sigma I^2(R + r)]}$. If now the power is evenly divided between the 8 wires, the current values in each wire will be represented by 2·74 (approx.) and the ratio of field strength at a distant point due to the two systems of current distribution will be 20/21·9 for equal power input. Thus ordinarily the losses due to uneven current distribution need not be great. In the foregoing discussion the assumption is made, though it is not entirely justifiable, that all radiators have the same resistance. Mr. Carter's assumption that the parallel arrangement of radiators in the Koomans type of array produces more even current distribution, is hardly justifiable. The horizontal radiators, built one above the other, branch from the same 2-wire vertical feeder. Obviously, therefore, to obtain equal currents correct matching should be installed at each feeding point. Owing to the reaction of one radiator on another, quarter-wave spacings would not greatly affect the gains. Moreover, since Mr. Carter has already stated that a horizontal Bruce type of array has a very uneven current distribution in its members, and has conjectured that such an unequal distribution in radiators arranged one above the other would be disadvantageous, his reasons for suggesting the erection of a Bruce array turned through 90° and so building vertical tiers of radiators are not apparent. The tests made by Mr. Carter on the reflector action of a single wire placed behind a second single exciter wire are interesting and, in a measure, constitute a reply to Dr. Smith-Rose. It is understood, however, that the reflector wire was maintained at the same length throughout the tests. The results would have been more convincing if various lengths had been used for each distance of the reflector wire from the exciter wire. Mr. Carter raises the question of the best width of a beam in a vertical plane for reception purposes. The subject is very controversial, and in the absence of exact knowledge of the various factors involved any opinion on the matter is merely conjectural. For the purpose of the arguments of this paper, Fig. 13, having spans shown as horizontal ordinates, seems to me to be the best arrangement.

I note the claim of Mr. Chireix respecting his patent, but am unable to comment on this matter. With regard to the reduced cost of a multi-wire and concentric copper tube line for transmission purposes, the ratio of 5:1 was based upon actual costs and certainly was not biased in favour of the multi-wire line. For reception purposes small-diameter copper tubes can be used, and in this case the ratio of costs is approximately unity. I am interested to notice the confirmation given by Mr. Chireix of the critical effect observed with reflector wires.

Captain Eckersley refers to some of the many factors involved in the economic design of a beam radio station. A few of the factors have already been mentioned in the paper, and obviously others would have to be considered when the design of a new station is involved. The problem is simplified when development only of an existing station is proposed. In England, the economics applicable to the design of a large new station are influenced by two facts—the number of available suitable sites is very limited, and the cost of land-line connections quickly decides the economic distance of the site from the control terminal office. Obviously, it is uneconomical to have the site far removed from main trunk lines, so that existing circumstances largely decide the location of the radio station. When, however, the question of the power required to be radiated in a desired direction is considered, circumstance is not so helpful. There are sometimes long periods during which satisfactory service can be maintained on relatively small power; there are frequent occasions when a manifold increase in power would not convert an uncommercial into a commercial service. Thus the decision upon the correct power to be radiated, and hence the best ratio of expenditure on arrays and transmitting plant, is fraught with difficulties almost beyond solution. Regarding the question of maintenance of aerials, low aerials have obvious advantages. So far as the Post Office aerials are concerned, the principle of thoroughness is observed in construction, and in consequence maintenance charges

due to broken wires and insulators are negligible. Moreover, the provision of a large telescopic ladder enables the greater part of the array described in the paper to be reached and thus efficiently maintained both as regards cost and time.

I was very gratified to see the communication of Mr. Franklin, whose pioneer efforts in short-wave beam working are remembered with admiration. Mr. Franklin quite correctly points out that there are limitations to the improvement in gain obtained by spacing one curtain of exciters half a wave behind the other. There is a slight narrowing effect both on the horizontal and vertical polar diagrams, but consideration of polar diagrams alone is equivalent to the assumption of 100 per cent radiation efficiency of the array. Dead-loss resistance, however, is appreciable and the higher this loss the nearer the field strength gain is simply proportional to the square root of the total number of radiators. I disagree with Mr. Franklin's contention that a more useful comparison of arrays could be made between the C type array having twice the height of curtain shown in Fig. 13, and the D type. The paper dwells upon the high cost of tall masts, and I definitely hold the view, both from theoretical and practical considerations, that the economic limit of height is quickly reached. Mr. Franklin refers to his scheme of folding wires to suppress radiation; the method which I described, whereby the current induced in a separate insulated wire is used to suppress unwanted radiation has been known for a long period and is believed to have originated in the Post office. As pointed out in the paper, the horizontal type of array has practically no side radiation, and suppression wires are therefore not required.

In reply to Mr. Franklin's general criticism, I can only assert that tests taken with local and distant transmissors show that the addition of a second exciter curtain used in the "T.W." type of array, is responsible for an additional improvement of about 2 decibels The account of the reasons responsible for the adoption of the concentric-tube type of feeder is interesting. Circumstances seem to have given Mr. Franklin no option in the matter. The simple truth, of course, is that the type of aerial employed, and shown diagrammatically in Fig. 2, is productive of large out-of-balance currents in open 2-wire transmission lines. As one line conductor is connected to the bottom of the aerial and the other to earth, obviously radiation from the open transmission lines would be very serious. The Post Office Engineering Department, realizing the value of symmetrically disposed radiators in an array, pinned their faith on open transmission lines. Results have entirely justified this policy. At a very small fraction of the cost of the concentric-tube line, high-efficiency lines have been built, possessing the advantages of easy and low maintenance charges.

Mr. Franklin states that with his type of aerial, overhead lines give rise to instability. This contrasts very unfavourably with the Rugby system. The fact is that the 16- and 33-metre services at this station using arrays fed through open lines 3 000 and 3 500 ft. long, respectively, with a feeder loss of about 30 per cent, are giving a service the frequency stability of which is unequalled. This must constitute my reply to Mr. Franklin's advocacy of concentric-tube lines.

Mr. Green draws attention to the apparent inconsistency in my reference to the reduction in resistance loss when three twin lines were used. In his arguments Mr. Green assumes similar lines, correctly terminated and having a surge impedance one-third that of a single twin line. All these assumptions are erroneous and therefore his conclusions fail. In his comments upon multi-wire lines, Mr. Green appears to have confused two factors—the relative ohmic loss of transmission lines having different surge impedances and the reduction in resistance loss obtained by dividing the copper in the limbs of a line whilst maintaining a definite surge impedance. The fact that low-impedance lines have greater ohmic losses than similar high-impedance lines for the same copper content was mentioned at the top of page 312 and hardly needs stressing. I did not suggest that multi-wire lines should be used as a substitute for 2-wire lines when radiation losses are low; I stated that multi-wire lines form an economical substitute for tube lines. The multi-wire lines can, of course, be arranged either in concentric or parallel lines. The point which I wished to bring out was that multi-wire lines built fairly close to the ground seem to reduce the radiation losses arising from unsymmetrical types of arrays. The possibility is that the unbalanced current, which must otherwise take a path via earth and transmitter capacitance, can, to a greater extent than is possible with single-wire lines, take the larger capacitance path between earth and line. In short, the multi-wire line tends to remedy the defect of unbalanced current due to unsymmetrically disposed radiators in an array.

Regarding the concluding remarks of Mr. Green, it is perhaps relevant to point out that telephone engineers are not unfamiliar with transmission-line problems and that much practical and theoretical work, both published and unpublished, has been undertaken since Oliver Heaviside first published his mathematical investigations into cable transmission problems. With regard to the comparatively simple application to radio engineering, correct scientific principles have been applied in general to problems of connection to aerial systems since Messrs. Beverage, Kellogg and Rice published the results of their theoretical and practical investigations in 1923.

I should like to express my sincere thanks for the very cordial reception given to my paper.